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Abstract

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Keywords

circular, experiments, apparatus, drawing, cups, deep, development, hydromechanical, micro, type, servo

Disciplines

Engineering | Science and Technology Studies

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Development of Servo-Type Micro-Hydropneumatic Deep-Drawing Apparatus and Micro Deep-Drawing Experiments of Circular Cups

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Abstract

A micro-hydropneumatic deep-drawing (MHDD) apparatus for manufacturing a micro-complex-shape components and increasing of drawn cup accuracy has been developed in this study. This apparatus with simple tooling structure and forming process can achieve high dimensional accuracy using servo press mechanics with a double-action type, one-stroke forming process without transferring and positioning, force control, and fine flow rate control of the pressure medium. The developed MHDD apparatus can prevent wrinkling by applying an appropriate constant gap and stably generate the counterpressure. Micro drawn cups of 0.8mm diameter are successfully fabricated. Also, the effects of counterpressure on drawability and dimensional accuracy at the bottom of the cup are investigated for phosphor bronze, stainless-steel, and pure titanium foils with a thickness of 50 μ m. The appropriate counterpressure applied in MHDD can eliminate wrinkling and reduce the frictional drawing force. It is concluded that the forming limit and dimensional accuracy can be improved by MHDD.

Highlights

- We develop a simple and servo type apparatus for micro hydropneumatic deep drawing (MHDD).
- One-stroke forming in which all forming processes can be carried out coaxially is adopted in MHDD process.
- High accurate micro cups with a diameter of 0.8 mm are successfully fabricated by MHDD.
- The generated stable fluid pressure can eliminate the wrinkling and reduce the frictional drawing force in MHDD.

Key words

micro sheet hydroforming, micro-hydropneumatic deep-drawing, servo press, counterpressure, forming limit, one-stroke forming.

1. Introduction

The demand for microcomponents with an ultrafine and complicated shape and high dimensional accuracy has been increasing in order to improve the performance of devices used in the fields of medicine, precision equipment, and communication, as well as achieve multifunctional, compact, and highly integrated devices (Geiger *et al.*, 2001). Generally, the dies with a high dimensional accuracy and complicated shape are required to form such microcomponents. However, as the miniaturization advances, the fabrication of these metal dies becomes difficult. In particular, there are limitations in terms of shape and dimension in fabricating metal dies with a complicated three-dimensional shape even when precision machining technology (using electron and ion beams) is adopted. Another issue is the decrease in the lubrication effect as the miniaturization advances (Engel, 2006). This is because the ratio of the open lubricated pockets area, on which lubricant cannot be maintained, with respect to the area in contact with the die **increases**. As a result, the forming limit decreases, the lifetime of dies shortens, and the surface property of the components deteriorates. In addition, the ductility and tensile

strength of metal foils decrease with decreasing thickness of workpiece. This is caused by an increase in the ratio of the grain size and surface roughness to thickness, leading to a deterioration of formability (Furushima *et al.*, 2014).

Micro-deep drawing (MDD) has been frequently used to fabricate microcomponents, and many researchers have carried out studies on its formability. Saotome *et al.* (2001) experimentally drawn cups (punch diameter $D_p = 1.0\text{--}10.0$ mm) using SPCE foils (thickness $t = 0.1$ mm). They clarified that the forming limit decreases with increasing the relative punch diameter to thickness (D_p/t). Chen *et al.* (2009) examined the effect of the ratio of thickness to grain size on the limit drawing ratio (LDR) by changing the grain size via annealing of SUS304 foils ($t = 0.02\text{--}0.15$ mm). They clarified that the LDR increases with increasing grain size or decreasing the ratio of sheet thickness to grain size for a given sheet thickness and that the theory of conventional macro-deep drawing cannot be applied to thin sheets. Vollertsen (2012) carried out an MDD experiment ($D_p = 1.0$ mm) using a pure aluminum sheet ($t = 0.02$ mm) and clarified that the lubrication was improved by increasing the punch speed, leading to an improvement of the fracture limit and expansion of the forming range. As explained above, the formability of MDD has been examined by many researchers. The LDR of conventional macro-deep drawing was approximately 2.2, however the LDR of MDD using foils with $t \leq 0.05$ mm was only approximately 1.8. Therefore, MDD involving die coating (Shimizu *et al.*, 2014), resistance heating (Tanabe *et al.*, 2011), and redrawing (Manabe *et al.*, 2008) has been carried out, as it is reported to improve the formability. Hu (2011) carried out MDD of pure aluminum foils ($t = 0.015$ and 0.020 mm) and successfully obtained microcups with a rectangular cross section (major axis, 1.5 mm; minor axis, 0.75 mm). Irthia *et al.* (2014) developed an MDD method with flexible dies obtained by including a rubber material in the die and succeeded in forming cups with an aspect ratio of 1.4 using SUS304 foils ($t = 0.06\text{--}0.15$ mm). Vollertsen *et al.* (2009) developed an MDD process with a pulsed laser, and succeeded in clarifying the mechanism behind the process and in forming microcups using pure aluminum, copper alloy, and stainless-steel foils ($t = 0.02$ and 0.05 mm). As explained above, research on the improvement of the formability and the forming of components with a complicated shape using flexible dies has been carried out; however, the formability obtained so far is still unsatisfactory and a forming process that satisfies both good formability and forming of components with a complicated shape has not been realized.

In this study, we focused on hydromechanical deep drawing (HDD) using counterpressure. With this forming method, components with a complicated shape can be formed because sheet materials are brought into smooth contact with the punch by applying a counterpressure using a male die alone, which is easily fabricated (Nakagawa *et al.*, 1997). In addition, the dimensional accuracy of the obtained components is improved (Nakagawa *et al.*, 1997). The forming limit is also improved owing to the friction holding effect, hydrodynamic lubrication effect (Nakamura *et al.*, 1984), and prebulging effect (Lang *et al.*, 2003). Furthermore, it was reported that an LDR of 3.31 is obtained by applying a radial pressure at the blank rim (Nakamura *et al.*, 1985) whereas LDR was only 2.33 for conventional deep drawing and 2.61 for general hydromechanical deep drawing. Therefore, hydromechanical deep drawing is considered to solve the problems related to micro forming explained above. However, there have been no reports on the application of hydromechanical deep drawing to micro forming to the best of our knowledge. The purpose of this study is to develop a micro hydromechanical deep drawing (MHDD) technology that may enable a semi-dieless process and improve the forming limit. A prototype MHDD apparatus was fabricated and the performance tests to realize the generation of counterpressure and the formation of microcups were carried out. The effect of the counterpressure on the forming limit of MHDD was experimentally clarified to evaluate the formability and shape accuracy of the components obtained by MHDD.

2. Design of MHDD apparatus

2.1 Design concept of MHDD apparatus

In order to design a press macroforming apparatus, the number of processes required to form components is determined and the processes are designed. Then, the dies, press apparatus, and transfer device required to perform the processes are prepared. However, there are design issues unique to microforming that must be overcome before the processes can be designed. In general, compared with the conventional macroforming, much higher accuracy is required for transfer, positioning, force, and stroke position controls. In addition, fine flow-rate control under high pressure is also required for micro hydroforming using fluid pressure. If an apparatus satisfying these advanced control requirements is designed using the conventional design concept of macroforming, the apparatus becomes large and costly, hindering the achievement of the saving of energy, space, and resources, which should be realized with microfactories. The design concept of the new MHDD apparatus includes simplification of the forming processes and apparatus structure, as shown in Fig. 1, through (1) adoption of one-stroke forming to avoid the need for material transfer and positioning control (coaxial multiple processes), (2) adoption of a constant gap method to avoid the need for highly accurate force control for preventing wrinkling, (3) sealing and generation of stable fluid pressure by decreasing the clearance between tools to avoid the need for

ultrafine flow-rate control, and (4) adoption of a multiaxis system inside the die to avoid the need for a double-action mechanical press and to simplify the apparatus structure. Through these measures, a simple apparatus is realized, which enables the fabrication of components with a high dimensional accuracy by decreasing the number of control targets.

2.2 One-stroke forming process

For the MHDD process that adopts the one-stroke forming process, in which all the forming processes are carried out coaxially, material transfer becomes unnecessary and high dimensional accuracy is realized. In addition, a highly accurate force control becomes unnecessary because of the adoption of the constant gap method instead of using the blank holder force (BHF), leading to high-speed and stable forming. However, the die cavity cannot be sealed by BHF or using the sealing material at the rim of the blank used to generate the counterpressure in the conventional method (Zhang *et al.*, 1998), as shown in Fig. 2(a) and (b), respectively. In addition, flow-rate control under high pressure is difficult. Therefore, the clearance between the die and the bush was made small, as shown in Fig. 2(c), to control the leakage of the pressure medium so that a stable fluid pressure can be generated without fine flow-rate control. Considering the feasible dimensional accuracy, we adopted a clearance of 1 μm for the MHDD die used in this study.

Fig. 3 shows the forming processes of the developed MHDD apparatus. (1) The drawing die (blanking punch) is fixed, whereas the upper die including the drawing punch, the blank holder, the blanking die, and the bush moves downward. In this stage, the clearance between the drawing die and the bush becomes small, as a result, the die cavity is sealed and a counterpressure is generated. (2) When the upper die moves further downward, the killer sheet integrated with the blank holder is fixed because of the killer pins, causing the blank holder to be simultaneously fixed. Thus, only the drawing punch, blanking die, and bush move downward during the blanking process. (3) During drawing, the drawing punch moves downward while maintaining a constant gap between the drawing die and the blank holder. By controlling the length of the killer pins, an arbitrary constant gap is maintained. (4) When the stroke reaches the bottom dead point, the upper die starts to move upward and the drawn cup is taken out knockout process. As explained above, the four processes, i.e., pressure generation, blanking, drawing, and knockout, are performed coaxially.

2.3 Outline of MHDD apparatus

Fig. 4 shows the schematic of the MHDD die and hydraulic system. In general, a multiaxial servo press is used for one-stroke forming, whereas the developed MHDD apparatus adopts a uniaxial servo press to perform one-stroke forming. Therefore, we design a die structure that can reproduce the behavior of a multiaxial servo press inside the die and simplify the structure of the entire MHDD apparatus. Each side of the MHDD die developed is as small as ~ 100 mm. The drawing die (blanking punch), blanking die, drawing punch, or bush is independently replaceable, accommodating various dimensions of components simply by changing individual parts. In addition, tools with a high dimensional accuracy were used; the tolerance of the blanking and drawing tools are ± 0.001 and ± 0.010 mm at the flat and curved parts, respectively. To measure the punch force, an ultrasmall compression-type load cell with a rating capacity of 50 N was incorporated in the die so that the force directly applied to the drawing punch is transferred to the load cell. In the hydraulic system, a relief valve to control the maximum counterpressure, a stop valve to suppress the rate of the flow into the die, and a hydraulic pump with a maximum counterpressure of 20 MPa were used. The desk top servo screw press machine shown in Fig. 5 was used with the MHDD apparatus. The specifications of the servo screw press machine were as follows: load capacity, 50 kN; die height, 130 mm; maximum stroke, 37 mm; positioning accuracy, 0.4 μm . Table 1 summarizes the specifications of the MHDD apparatus.

3. Determination of appropriate tool dimensions by performance test of MHDD apparatus

The performance test of the MHDD apparatus was carried out to examine its operation and determine appropriate tool dimensions to prevent wrinkling and generate a counterpressure.

3.1 Materials used and test conditions

Phosphor bronze foils (C5191-H) with thickness t_o of 20 and 50 μm were used in the experiment. Fig. 6 shows the dimensions of the die and the scale factors $\lambda = t_o/t_{ref} = 2/5$ and 1 were adopted on the basis of the law of geometric similarity. At $\lambda = 2/5$, a punch shoulder radius r_p of 0.04 or 0.25 mm was used. Cups with a drawing ratio D_o/D_p of 1.74 were targeted. To examine the effect of the constant gap on the wrinkling, experiments were carried out under five conditions, constant gap $h = 1.10t_o, 1.20t_o, 1.30t_o, 1.40t_o$, and $2.40t_o$ by conventional MDD in dry friction. For MHDD, a forced pressurization was adopted using hydraulic oil (40 $^\circ\text{C}$, 44 mm^2/s) as a pressure medium. The temperature was controlled by cooling the hydraulic oil with water. The drawing rate was 0.4 mm/s.

3.2 Determination of appropriate constant gap to prevent wrinkling

Fig. 7 shows the effect of the constant gap between the blank holder and the drawing die on the punch force-stroke curves (P_H - s curves). At $h = 1.10t_o$, a normal P_H - s curve is obtained. The constant punch force observed in the latter half of the forming process is the sliding force generated as a result of the sliding of the cup edge against the die side wall. At $h > 1.10t_o$, ironing force **of wrinkles** is observed after the force reaches the maximum; the ironing and the sliding forces increase with increasing constant gap. When the cups formed at $h = 1.10t_o$ and $2.40t_o$ are compared, flange wrinkles are observed in the cups formed at $h = 2.40t_o$, whereas wrinkles are generated only at the cup edge at $h = 1.10t_o$ with reduced wrinkles height. This result indicates that for large gaps, the blank holder does not function properly, leading to the generation of flange wrinkles. When the flange wrinkles are crushed, the ironing force is generated and the sliding force increases. For small gaps, in contrast, the blank holder functions properly, which reduces the wrinkles height, leading to the suppression of the ironing force and reduction in the sliding force. Under the forming conditions adopted in this study, the appropriate constant gap was determined to suppress the wrinkling, although it was impossible to completely prevent wrinkling by controlling the constant gap. For the developed MHDD apparatus, $h = 1.10t_o$ was adopted.

3.3 Determination of appropriate clearance for generating counterpressure

Fig. 8 shows the counterpressure-stroke curve and the punch force-stroke curve during the MHDD process. As shown in Fig. 3, the forming processes consist of (1) counterpressure generation, (2) blanking, (3) drawing, and (4) pressure release and knockout. Stable counterpressure was found to be generated during drawing when the clearance between the drawing die and the bush was set to $1\ \mu\text{m}$. The counterpressure did not decrease during the drawing process, which proves that the pressure medium did not leak from the blank rim. Namely, the process is a radial pressure-aided deep drawing by an indirect method in which a compressive force is applied from the blank rim radially inward (Nakamura *et al.*, 1985). By this method, the friction force is reduced by the leakage of pressure medium between the blank and blank holder and the meridional stress is also reduced.

3.4 Drawn cups

Fig. 9 shows drawn cups obtained under different scale factors (λ) and punch shoulder radii (r_p) for MDD and MHDD. At $\lambda = 2/5$ and $r_p = 0.04\ \text{mm}$, the cups was unsuccessfully drawn. At $\lambda = 1$ and $r_p = 0.10\ \text{mm}$ or $\lambda = 2/5$ and $r_p = 0.25\ \text{mm}$, the cups was successfully drawn for both MDD and MHDD. Therefore, the MHDD apparatus can be used to form microcups with diameters $\leq 1\ \text{mm}$. Fig. 10(a) shows the appearance of microcups obtained by MDD and MHDD. The drawn microcups with diameters of 0.8 and 2 mm are smaller than a rice grain. Fig. 10(b) shows a cross section of a drawn cup. The microcup was successfully drawn even at $\lambda = 1$ and a sharp punch shoulder of $r_p = 0.10\ \text{mm}$.

The above results confirmed that the MHDD apparatus with a simple tooling structure and forming processes realized the required performance without the need for large and expensive equipment.

4. Effect of counterpressure in MHDD

4.1 Effective punch force

Phosphor bronze (C5191-H), stainless steel (SUS304-H), and pure titanium (TR270C-H) foils with a thickness $t_o = 50\ \mu\text{m}$ were used. Table 2 lists the mechanical properties of the three materials obtained by the tensile test. The tool dimension shown in Fig. 6 was used, and scale factor $\lambda = 1$ and constant gap $h = 1.10t_o$ were adopted. For MHDD, forced pressurization was adopted using machine oil as the pressure medium. MDD was carried out without lubricant. The drawing rate was $0.4\ \text{mm/s}$.

To evaluate the change of frictional force in MHDD, effective punch force (P_E) was calculated by subtracting the counterpressure force to push back the punch (F_H) from the measured punch force (P_H) as

$$P_E = P_H - F_H = F_S + F_B + (F_{FDie} + F_{FBH}) \quad (1)$$

where, F_S is the pure drawing force at the flange, F_B is the bending force at the die shoulder, F_{FDie} is the friction force between the blank and the die, and F_{FBH} is the friction force between the blank and the blank holder. **In the same tooling conditions, F_S and F_B can be considered to be almost equal even if the fluid pressure increases. Therefore, the change of effective punch force shows the change of friction force. Thus, even though F_S and F_B is unknown, the difference in the friction force can be evaluated by the difference of P_E .**

4.2 Effect of counterpressure on forming limit during MHDD

Fig. 11 shows the appearance of cups of the three materials, fabricated by MDD and MHDD. For stainless steel, wrinkling occurred at the cup edge even for appropriate constant gaps in MDD. In contrast, wrinkling was suppressed at the cup edge obtained by MHDD with applying counterpressure of 15 MPa. The applying counterpressure causes the blank to be pushed against the blank holder. This compressive force acts as the suppressive force of wrinkling. However, when the counterpressure was increased to 20 MPa in MHDD, the cup was fractured at the punch shoulder. The wrinkling prevention effect by the applying counterpressure during MHDD can be observed for all of the three materials and at $\lambda = 2/5$ (Fig. 9).

Fig.12 shows the effect of counterpressure on normalized maximum effective punch force and normalized counterpressure relations for various materials. **The effective punch force is normalized to cup cross section at side wall ($\pi^*(D_p+t_0)^2 t_0$) and tensile strength σ_B . The maximum possible punch force is expressed by $(\pi^*(D_p+t_0)^2 t_0) \sigma_B$. Thus, the normalized maximum effective punch force can be written for different blank materials by the above maximum possible punch force.** For the stainless-steel foil, the maximum effective punch force decreases with applying the counterpressure. The difference in the effective punch force represents the difference in the friction force. By applying the counterpressure, the friction force decreases, improving the lubrication. However, the maximum effective punch force increases when the counterpressure is further increased. This is because the blank is pushed against the blank holder by the counterpressure, which increases the friction force. From this result, the fracture at the punch shoulder under high pressures is considered to be caused by the excessive friction force at the flange. This behavior is observed in all of the three materials.

Fig. 13 shows the effect of counterpressure on the occurrence of wrinkling and fractures during MHDD. When the counterpressure normalized by Young's modulus (p/E) is smaller than a certain value, wrinkling occurs (wrinkling zone), whereas the cups fracture when p/E is larger than a certain value (fracture zone). When p/E falls between these two values, cups without wrinkles or fractures are obtained (success zone). For the pure-titanium foil, the size of wrinkles decreases with applying the counterpressure (Fig. 11); however, the cups fracture before wrinkles are completely removed, not showing the success zone. This is because the friction force for the pure-titanium foil becomes too large and the fracture zone shifts to the low-pressure side, leading to the fracture zone merging with the wrinkling zone and the disappearance of the success zone. The success zone for pure-titanium foils may be obtained by improving the lubrication to decrease the friction force and shift the fracture zone to the high-pressure side. The limit blank holding pressure in cylindrical deep drawing normalized by Young's modulus is predominantly determined by the tool dimensions alone (Kawai *et al.*, 1960). The existence of a wrinkling zone at a certain p/E or less under the same tool conditions means that the counterpressure in MHDD functions equivalently to the blank holder. From the above, the applying appropriate counterpressure in MHDD is considered to prevent the wrinkling and reduce the friction force, leading to the improvement of the forming limit.

4.3 Improvement of shape accuracy by applying counterpressure

Fig. 14 shows the effect of applying counterpressure on the shape accuracy at the bottom of cups. The bottom obtained by conventional MDD is convex with respect to the punch, whereas the bottom obtained by MHDD with the application of counterpressure is concave; thus, the bottom shape obtained by MDD is different from that obtained by MHDD. In addition, the concave deformation toward the punch increases with increasing counterpressure during MHDD. In conventional MDD, the bottom of the cup is subjected to bulge deformation by the bending moment during deep drawing, resulting in a convex shape with respect to the punch, as shown in Fig. 15. In contrast, when the fluid pressure that counters the bending moment is applied to the bottom during MHDD, the convex bulge deformation is suppressed and a flat cup bottom is formed. However, the degree of adhesion between the punch and the blank is increased by increasing the counterpressure and a negative pressure is generated during the knockout process. The counterpressure is continuously applied until the end of the knockout process, leading to a concave shape with respect to the punch. The negative pressure can be suppressed by making a hole at the center of the punch or a small groove on the side wall of the punch. The concave cup bottom obtained by MHDD can be made flat by controlling the tool and forming conditions. These results confirmed that the shape accuracy of the microcups is improved by applying counterpressure during MHDD.

5. Conclusions

In this study, we developed an MHDD apparatus with the concept of realizing high dimensional accuracy of drawn components by minimizing the number of control targets, using an apparatus with simple forming processes and tooling structure. The following conclusions were obtained.

- 1) A servo-type MHDD apparatus with a simple structure and a small-clearance die structure was successfully developed which can reproduce a multiaxial press by one-stroke forming and the constant-gap method.
- 2) It was confirmed that the developed MHDD apparatus can prevent wrinkling with a constant gap of $h = 1.10t_0$ and generate a counterpressure with a clearance between tools of $1\text{ }\mu\text{m}$ that is sufficient to achieve a stable sealing. The microcups with a diameter of 0.8 mm and a sharp cup with a diameter of 2.0 mm and a punch shoulder radius of 0.1 mm were successfully formed.
- 3) When the counterpressure normalized by Young's modulus (p/E) is smaller than a certain value, wrinkles are generated. When the counterpressure is too large, the friction force increases, causing the fracture of **cups** at the punch shoulder. The applying appropriate counterpressure eliminates the generation of wrinkles and reduces the frictional force, leading to the improvement of the forming limit.
- 4) The cup bottom obtained by MDD is convex with respect to the punch. In contrast, the cup bottom obtained by MHDD with applying the counterpressure is concave. The dimensional accuracy of the MHDD process can be improved by adopting measures such as air venting.

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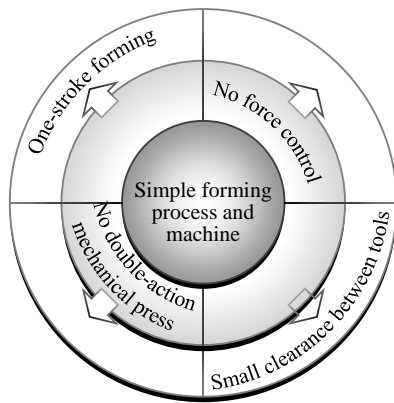


Fig. 1 Design concept of new MHDD apparatus.

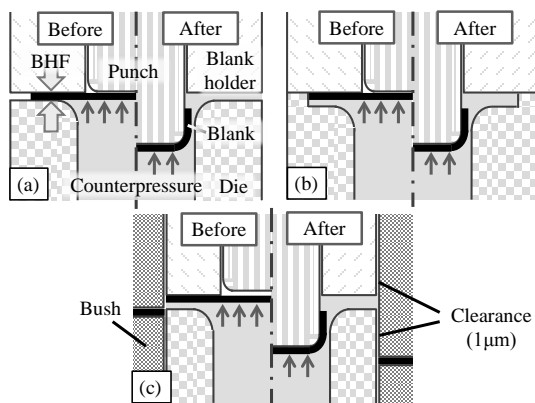


Fig. 2 Schematic of pressure generation methods (a) BHF in HDD, (b) sealing at blank rim in HDD, (c) small clearance between drawing and blanking tools in MHDD.

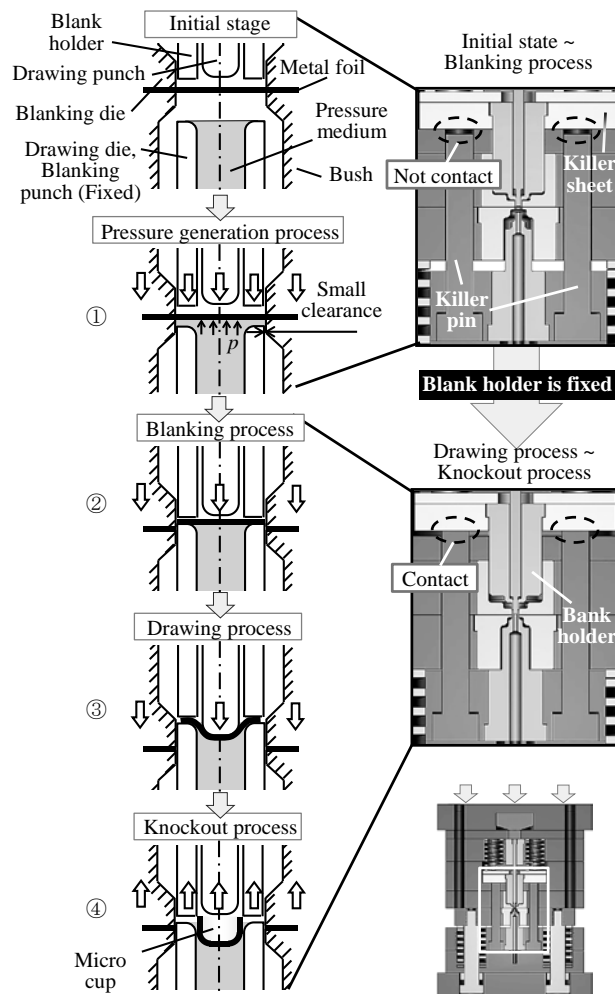


Fig. 3 Schematic of MHDD processes and movement of tool.

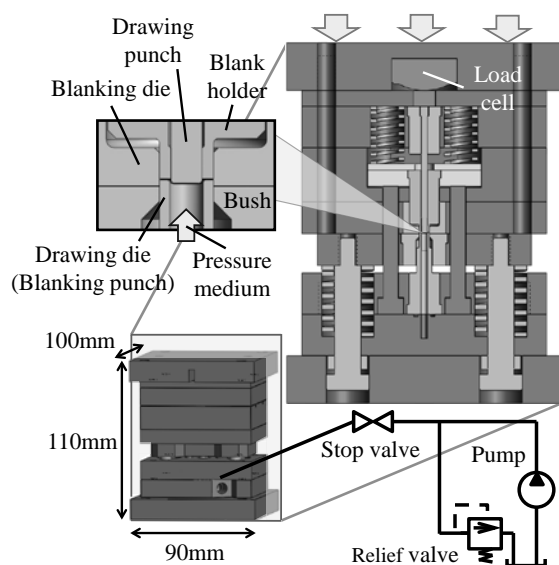


Fig. 4 Developed micro-hydraulic deep-drawing tool set and hydraulic system.

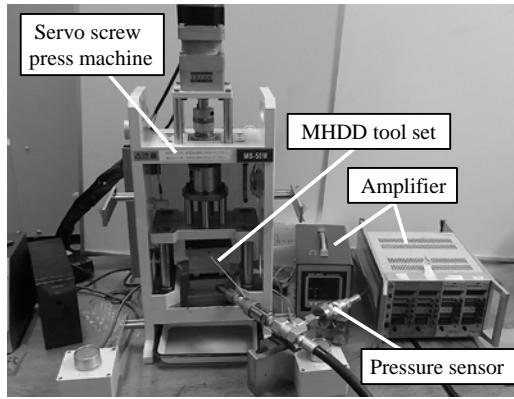


Fig. 5 Newly developed MHDD system with servo screw press apparatus.

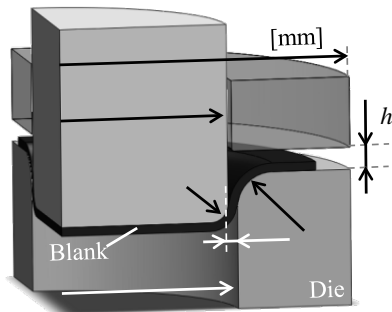


Fig. 6 Tool dimensions for micro deep-drawing ($\lambda=2/5, 1$).

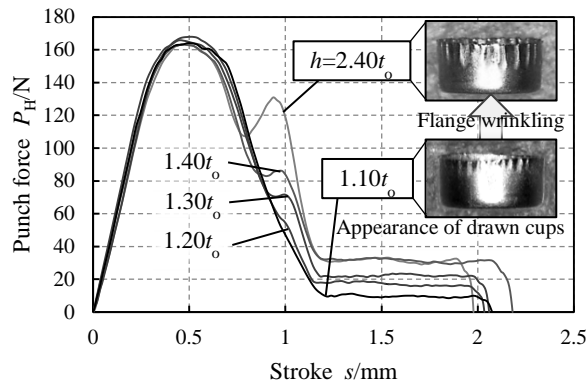


Fig. 7 Effect of gap between blank holder and drawing die on punch force-stroke curve (Phosphor bronze, C5191-H).

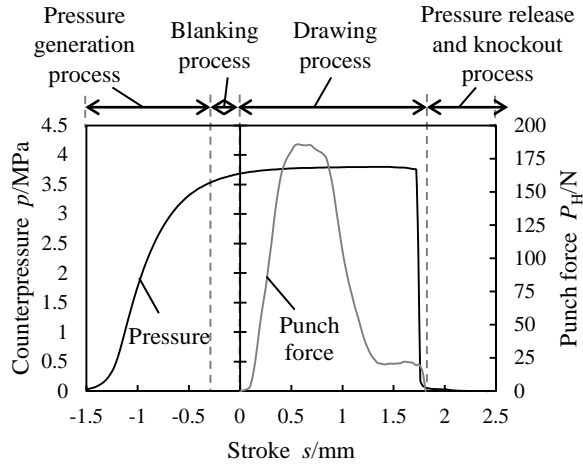


Fig. 8 Counterpressure- and punch force-stroke curves during MHDD process.

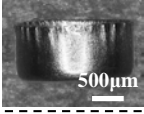
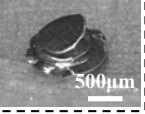
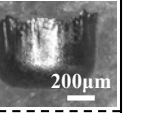
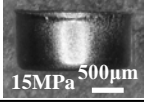
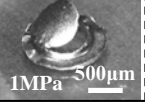
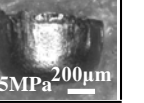
	$\lambda=1$ ($D_p=2.0\text{mm}$)		$\lambda=2/5$ ($D_p=0.8\text{mm}$)	
	$r_p=0.10\text{mm}$		$r_p=0.04\text{mm}$	$r_p=0.25\text{mm}$
MDD				
MHDD				

Fig. 9 Drawn cups under different scale factors and punch shoulder radii in MDD and MHDD (λ : scale factor).

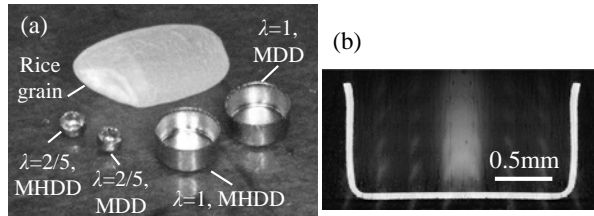


Fig. 10 Appearance of drawn cups in MDD and MHDD (a) different scale cups around a rice grain, (b) axial cross section of drawn cup ($\lambda=1$, $D_p=2.0\text{mm}$).

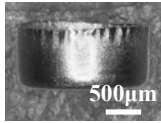
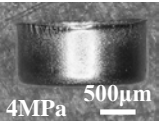
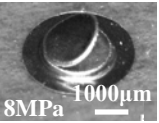
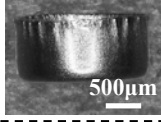
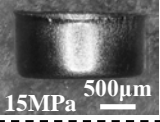
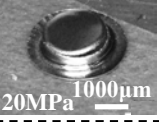
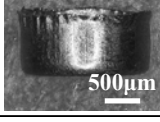
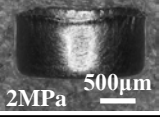
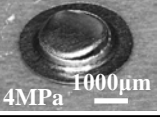
	MDD (Wrinkling)	MHDD (Success)	MHDD (Fracture)
Phosphor bronze	 500μm	 4MPa 500μm	 8MPa 1000μm
Stainless- steel	 500μm	 15MPa 500μm	 20MPa 1000μm
Pure titanium	 500μm	 2MPa 500μm	 4MPa 1000μm

Fig. 11 Appearance of wrinkling, success and fracture cups in MDD and MHDD for various materials.

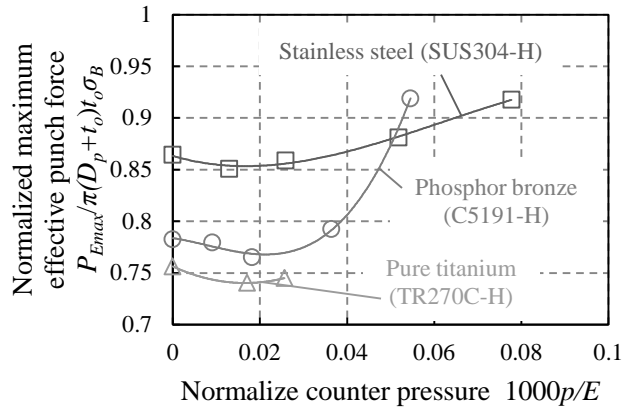


Fig. 12 Effect of counterpressure on normalized punch force for various materials.

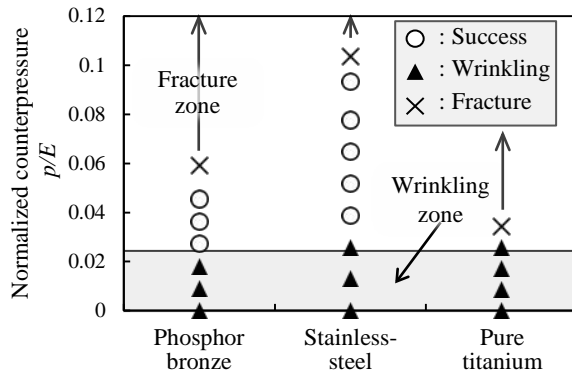


Fig. 13 Effect of normalized counterpressure on occurrence of wrinkling and fracture in MHDD.

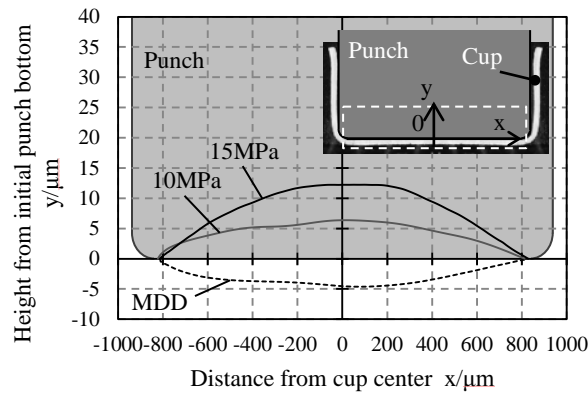


Fig. 14 Effect of counterpressure on drawn cup profile at the bottom of the cup (Stainless-steel).

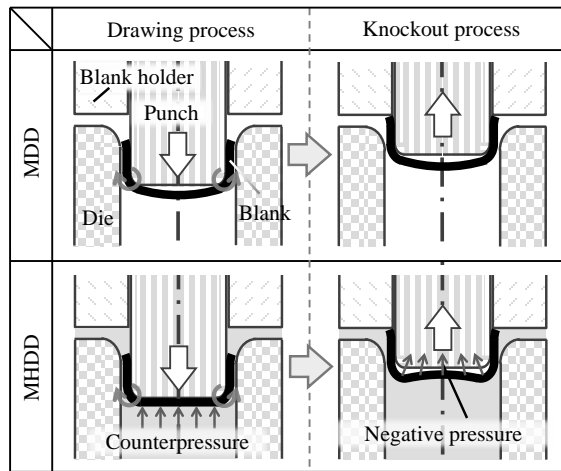


Fig. 15 Comparison of blank deformation at punch bottom in MDD and MHDD.

Table 1 Specification of developed MHDD apparatus.

Specification of MHDD apparatus			
Main MHDD system	Servo screw press machine	Load capacity /kN	50
		Motion resolution /nm	400
	Hydraulic system	Pump pressure /MPa	20
Tooling	Forming process	1-stroke forming	
	Blank holder	Constant gap method	
	Pressure generation	1μm clearance between tools	
	Tolerance	Flat part /mm	±0.001
		Radius part /mm	±0.01

Table 2 Mechanical properties of materials used.

Material	Young's modulus E /GPa	Yield stress σ_y /MPa	Tensile strength σ_b /MPa	Elongation δ /%
Phosphor bronze (C5191-H)	110	610	682	0.6
Stainless-steel (SUS304-H)	193	1217	1331	2.4
Pure titanium (TR270C-H)	117	601	807	1.4